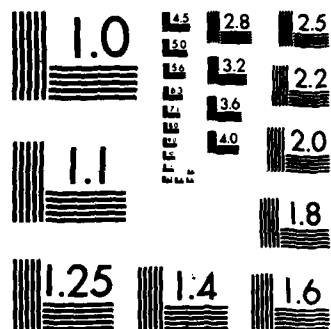END

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RESIDUAL STRESS MEASUREMENT IN CIRCULAR STEEL CYLINDER

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MAY 1984

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Hoop residual stresses in a right circular steel cylinder were determined by ultrasonic velocity measurements. The zero stress position was obtained from an equilibrium condition, setting the integrated tensile equal to the integrated compressive hoop stress. Absolute stress values were obtained with the help of calibration measurements on a rectangular test bar of the same material, which was subjected to known applied forces. The stresses determined
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20. ABSTRACT (CONT'D)

from these ultrasonic velocity measurements are in good agreement with values
obtained by x-ray diffraction analysis of lattice strains.

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INTRODUCTION

It has been long realized that residual stresses in structures can have significant effects on fatigue life. X-ray methods were the earliest quantitative techniques which were used to determine surface residual stresses. Ultrasonic velocities, on the other hand, are sensitive to bulk residual stresses, and may often be simpler and more appropriate to use. In this work we present stress measurements obtained using the ultrasonic method and compare them with the results obtained for the same specimen using x-ray techniques. The close agreement between the results of the two methods gives us a measure of confidence in our methods and assumptions.

The theory of ultrasonic velocity changes due to finite strain has been worked out by Hughes and Kelly (ref 1). These finite strains are associated with residual stresses, and higher order elasticity theory is used to obtain the stress-strain relationships, as well as the effect of the stresses on the longitudinal and transverse ultrasonic velocities. The present method for measuring residual stresses through velocity change measurements is accurate, quick, and straightforward, and does not require extensive training.

EXPERIMENTAL DETAILS

Two specimens were used in this work. The stress measurements were performed on a pre-stressed right circular, hollow cylinder 1-7/8 inches thick with an inner and outer diameter of 6-3/8 and 12 inches, respectively. Calibration measurements were carried out on a rectangular test bar of cross-

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[1]Hughes, D. S. and Kelly, J. L., "Second Order Elastic Deformation of Solids," Phys. Rev. 92, 1953, p. 1145.

1

sectional area one-half by one-half inch identical in material and cold work directionality to the cylinder. The faces of the test bar as well as the top and bottom faces of the cylinder were ground flat and parallel to better than .0001 inch per inch for the ultrasonic measurement. A 5 MHz shear transducer was placed on a flat face with a high viscosity liquid bond. Shear wave velocity measurements were made as a function of radial position between the inside and outside diameter for the cylinder, and as a function of applied external stress for the test bar.

For our specimens, since the faces which reflect the ultrasonic signal are parallel, any change in velocity can be determined from the change of return time of an echo. The fifth echo was normally chosen as a compromise between the increased accuracy that can be obtained by choosing later echoes versus a reasonable amplitude required for making readings obtained from the earlier echoes. The change in velocity was simply measured by visually observing the change in return time on an oscilloscope screen as a function of stress. The resolution of the return time measurement was better than 5 nsec ($5x10^{-9}$ sec). For the calibration specimen the change in thickness and in area with applied tensile force was also measured to determine velocity and stress. The oscilloscope had a variable delay and a time expander so that any portion of the echo train could be expanded. As time reference we used, in the case of the test bar, the return time for the echo at zero stress, and for the cylinder, the return time at the outer diameter. Only velocity differences are considered here.

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STRESS VELOCITY RELATIONS

Residual stresses are associated with the Lame´ constants of linear
elasticity and also higher order elastic constants from the theory dealing
with finite deformations. The analysis treats the ultrasonic wave, which is
an infinitesimal periodic deformation, as superimposed on a residual stress
which is a static finite deformation of the medium. The ultrasonic wave
velocity is sensitive to these stresses. The greatest sensitivity to uniaxial
stresses is shown by polarized shear waves, where the direction of propagation
is perpendicular and the polarization is parallel to the stress direction.

Equation (1), adapted from Hughes and Kelly (ref 1), gives the shear
velocity V_2 for an ultrasonic wave propagating in an isotropic medium along
the 1-axis and polarized in a direction perpendicular to it (arbitrarily
chosen as the 2-axis).

$$\rho_0 V_2{}^2 = \mu + \frac{1}{3K_0} \, [(3\lambda+2\mu)\sigma_1$$

$$+ (3\lambda+2\mu + \frac{3n\lambda}{4\mu} + \frac{n}{2})(\sigma_1+\sigma_2)$$

$$+ (m - \frac{n}{2} - 2\lambda - \frac{n\lambda}{2\mu})(\sigma_1+\sigma_2+\sigma_3)] \tag{1}$$

Here, $K_0 = \lambda + 2\mu/3$ is the compressibility, λ and μ are the Lame´ constants,
and m and n are Murnaghan's second order elastic constants, as defined in
Hughes and Kelly. The σ's are the finite triaxial principal stresses along

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[1]Hughes, D. S. and Kelly, J. L., "Second Order Elastic Deformation of Solids,"
Phys. Rev. 92, 1953, p. 1145.

the direction of propagation and perpendicular to it. Equation (1) has also been derived by Bach and Askegaard (ref 2). It can be seen from Eq. (1) that the sound velocity of the shear wave is, in principle, affected by all three principal stresses. Thus, it may be necessary in general, to experimentally determine the factors multiplying the stresses in Eq. (1).

EXPERIMENTAL METHODS

In order to determine the factors in parentheses multiplying the stresses in Eq (1), measurements were performed on a rectangular test bar. A force was applied along its length and the velocity of the shear waves polarized parallel and perpendicular to the stress and propagating perpendicular to it were measured. For these experimental conditions, $\sigma_1 = 0$. Figure 1 shows the stress-velocity relationship for the two polarization directions. There is essentially no change of the velocity of the shear wave polarized perpendicular to the stress direction with applied stress, indicating that the factor $(m - n/2 - 2\lambda - n\lambda/2\mu)$ in Eq. (1) is essentially zero for the material investigated here. Thus, setting $V_2 = V_{2o} + \Delta V_2$ and $\rho_o V_{2o}^2 = \mu$ we can reduce Eq. (1) to

$$\frac{\Delta V_2}{V_{2o}} = \frac{1}{6\mu K_o} (3\lambda + 2\mu + \frac{3n\lambda}{4\mu} + \frac{n}{2})\sigma_2 \qquad (2)$$

where the factor in front of σ_2 is obtained from the test bar measurements for the change in shear velocity with polarization parallel to the applied tensile stress, as a function of tensile stress (Figure 1). The uncertainty in time

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[2]Bach, F. and Askegaard, V., "General Stress-Velocity Expressions in Acousto-elasticity," Exp. Mech. 19, 1979, p. 69.

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together with the cross-sectional dimensions of the test bar result in a $\pm$ 1% uncertainty in the change of velocity with tensile stress for this case.

Stress measurements on the cylinder were made for waves propagating parallel to its axis and polarized perpendicular to its radius, i.e., along the hoop direction. Figure 2 shows the change in return time of the fifth echo of an echo train generated by the 5 MHz shear transducer whose polarization direction is in the hoop direction. The time increments were measured taking the slowest return time as a reference. The procedure was to choose one echo (the fifth), display it at the right hand side of the cathode ray tube by using the variable delay and the 20 nsec/cm oscilloscope sweeprate, while the transducer is at the position for greatest tensile residual stress. Then, as the transducer moved across the specimen from the outside to the inside diameter, the change in return time of the echo is noted as it moves across the screen.

In order to correlate the time changes with the actual stress we need a way of establishing the zero stress position. For a hollow cylinder of inner and outer radius a and b, respectively, equilibrium conditions require that the integrated hoop stress

$$\int_a^b \sigma_H dr = 0.$$

Therefore, we can determine the zero residual stress level by balancing the tensile and the compressive hoop stresses as indicated in Figure 2.

Because of various directional properties of the material before the cold working, we did not expect that the zero residual stress position would yield elastic constants that are indicative of the material in its isotropic state;

but the zero residual stress position found in this manner is the zero for the residual stresses imposed by the cold working (autofrettage) process.

The hoop stresses can now be determined with the help of Eq. (2) in combination with the calibration data (see Figure 2). Since the cylinder is short, the assumption implicit in Eq. (2) that $\sigma_1 = 0$ can be considered valid. Here we also assumed that the linear relationship between change in velocity and tensile stress could be extended for compressive stresses with the same slope (ref 3).

Figure 3 shows the results. Also shown for comparison are the ults of x-ray studies to measure the residual stress (ref 4). The latter ⁓ were obtained by using a stress goniometer. The stress values were obt . ' from the product of the x-ray elastic constant (measured independently) and the slope of the least squares line of strain vs. $\sin^2\psi$ (ψ is the angle of inclination with the normal).

CONCLUSIONS

The results of the two methods agree to a remarkable degree, thus giving us confidence that the methods described can be used to obtain residual stresses in industrial components made of steel. The ultrasonic method is quick, simple, and accurate. The specimens must have two parallel faces and the stresses must be independent of distance from these faces. If the zero

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[3]Holler, P., "Structure and Stress Analysis of Steels by Ultrasonic and Micromagnetic Methods," Symposium on Nondestructive Methods for Material Property Deformations, Hershey, PA, 6-8 April 1983.
[4]Capsimalis, G. P., Haggerty, R. F., and Loomis, K., "Computer Controlled X-Ray Stress Analysis for Inspection of Manufactured Components," Technical Report WVT-TR-77001, Watervliet Arsenal, Watervliet, NY, January 1977.

stress position is to be found, then additional information must be brought in, as in our case, the balance of forces. Then, the changes in shear wave velocity can be taken with respect to that position to evaluate the actual positive or negative stress values. This assumes a linear superposition of velocities due to stresses and other extraneous effects which may result from previous heat treatment or cold working. The methods given here will be even more effective for metals like aluminum which have a larger velocity stress coefficient and lower attenuation than steel.

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    Solids," Phys. Rev. 92, 1953, p. 1145.

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    Acoustoelasticity," Exp. Mech. 19, 1979, p. 69.

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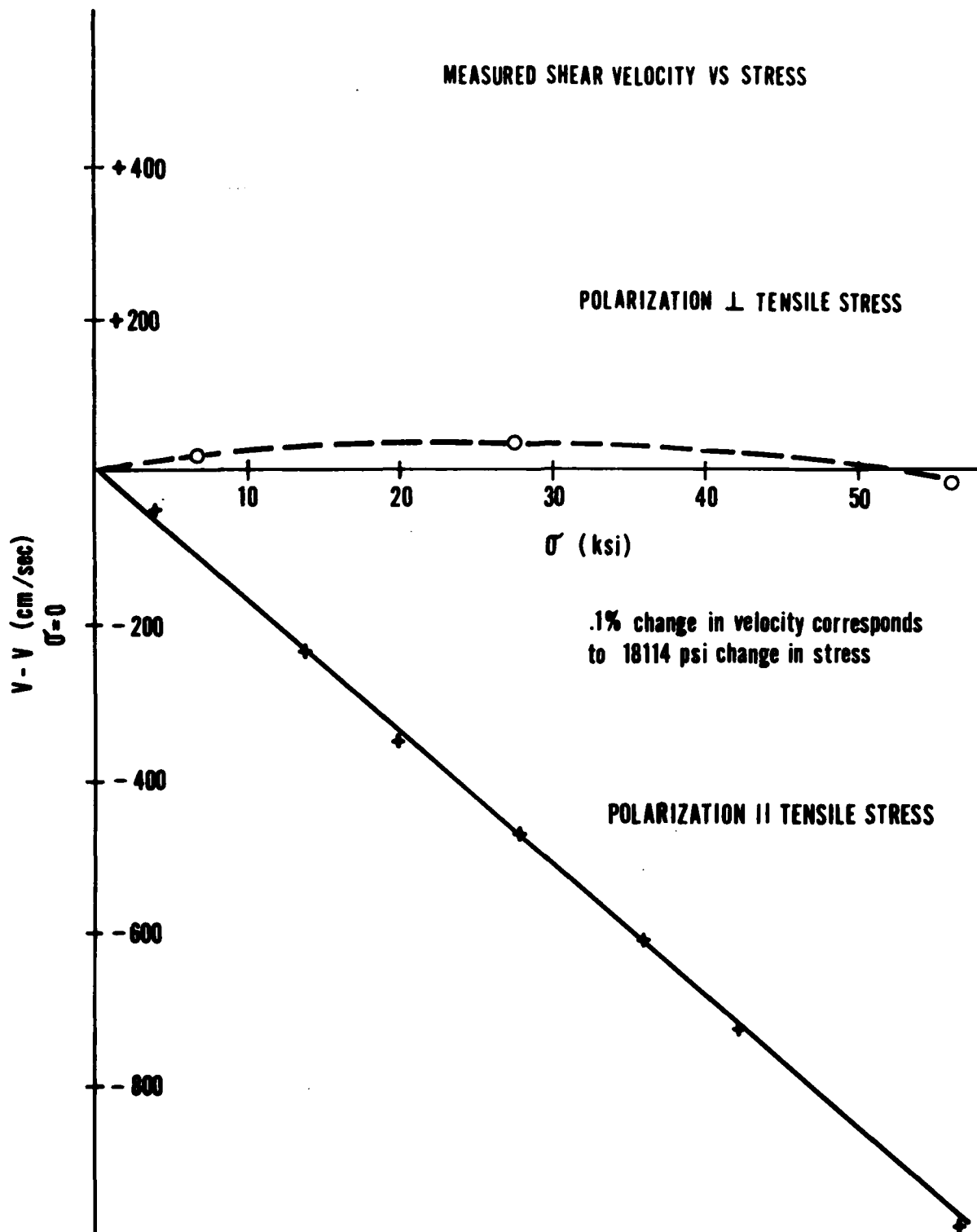   Report WVT-TR-77001, Watervliet Arsenal, Watervliet, NY, January 1977.

Figure 1. Change in Velocity With Applied Tensile Stress for the Calibration Specimen
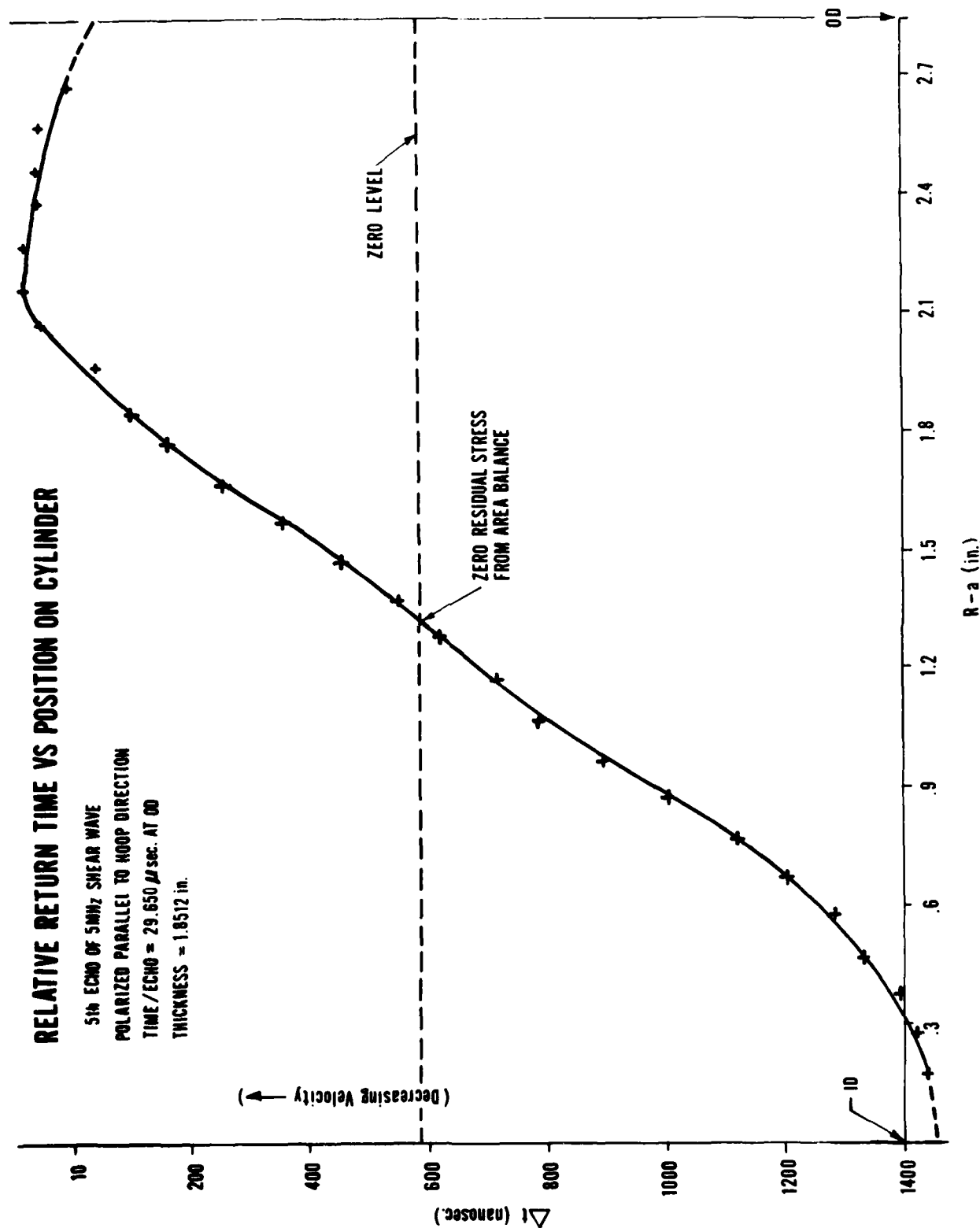
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Figure 2. Change in Return Time vs. Radial Position of Fifth Echo for the Hollow Cylinder. ID and OD Denote the Inner and Outer Diameter, Respectively.
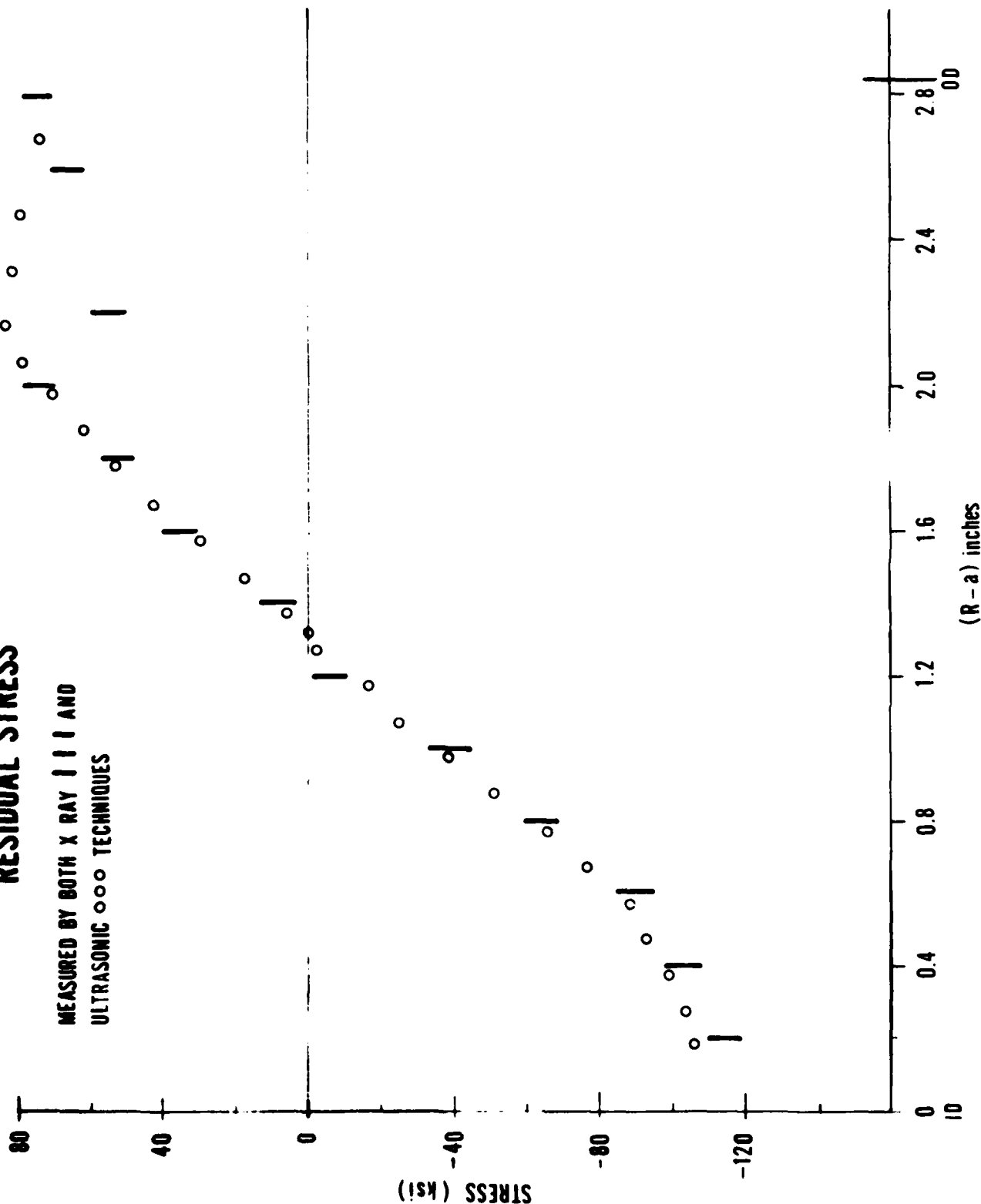
Figure 3. Comparison of Residual Hoop Stresses Computed From Ultrasonic and X-Ray Measurements.

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